Beyond the SM Models at the Tevatron and LHC

"A (brief and not unweighted) random walk through the theory landscape"

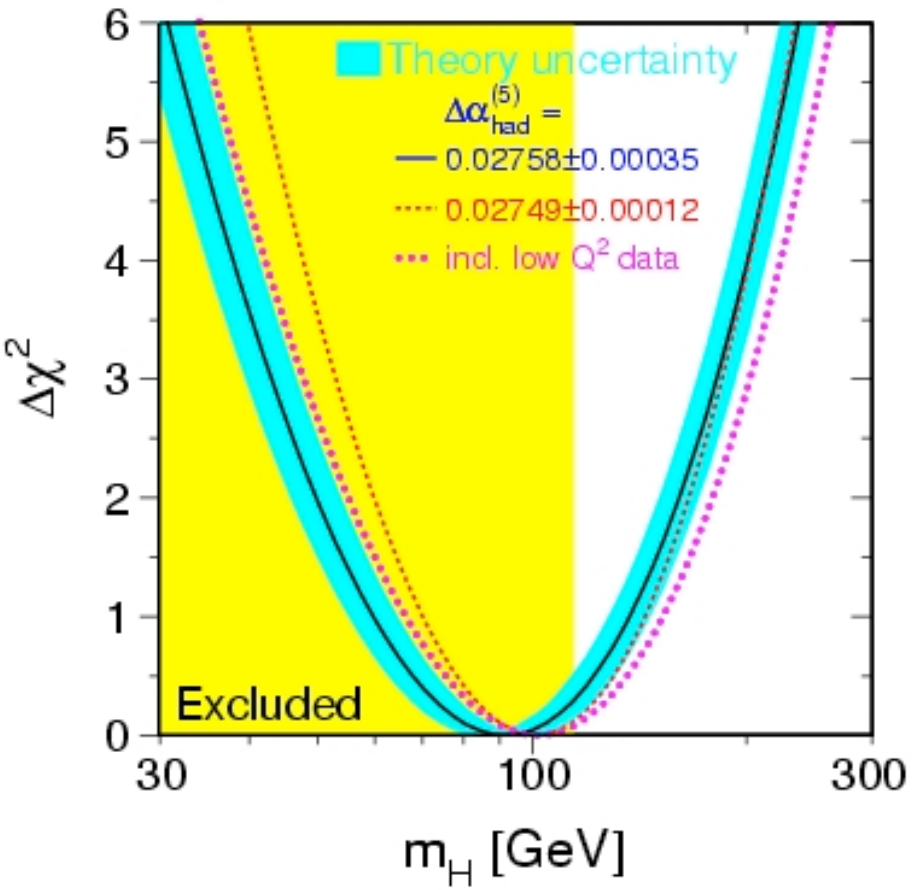
M. Perelstein, Cornell

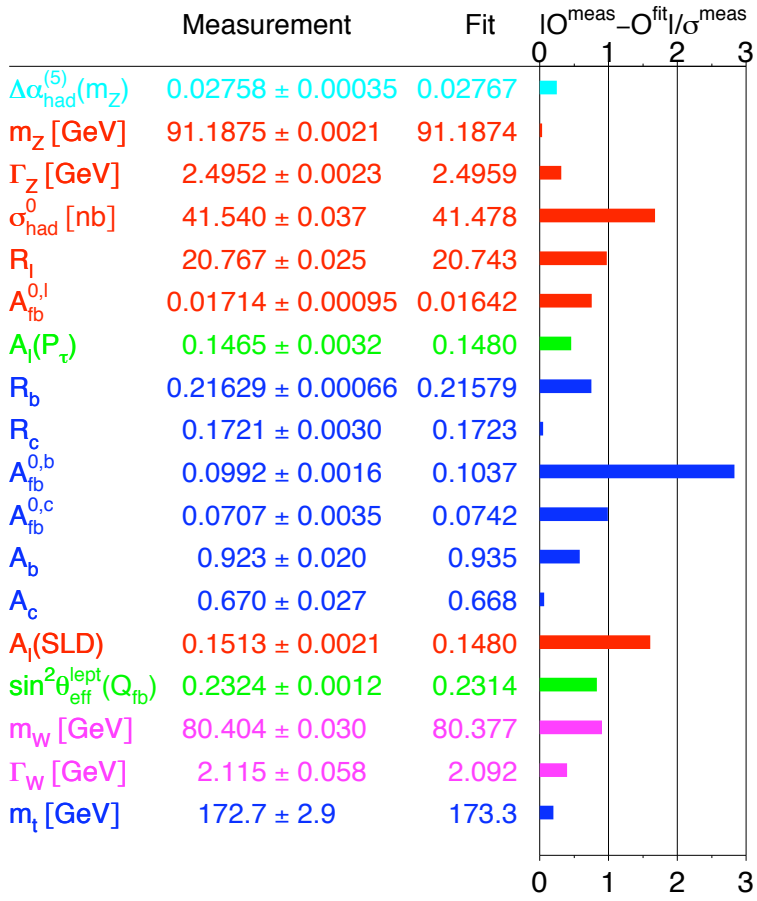
HCP 2008 Workshop, May 29 2008

Introduction

- Standard Model: Electroweak gauge symmetry SU(2)xU(1) is fundamental, but spontaneously broken at low energies down to e&m U(1)
- Uncovering the mechanism of electroweak symmetry breaking (EWSB) is the central question for the LHC
- The Standard Model explanation of EWSB: Higgs phenomenon
- Postulate a new particle - the Higgs boson - of spin 0
- Vacuum is filled with Higgs condensate, which breaks the symmetry

Is the Higgs Really There?





- Standard Model with a light Higgs provides a good fit to all data, indirect determination of H mass:

$$M_H < 186 \text{ GeV} \quad (95\% \text{ c.l.})$$

Light Higgs ⇨ New Physics

- No elementary spin-0 particles are known to exist: scalar mass is unstable with respect to radiative corrections

- In SM, $V(H) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$

$$v^2 = \frac{\mu^2}{\lambda}, \quad m_h^2 = 2\mu^2$$

- Renormalization:

$$\mu^2(M_{\rm ew}) = \mu^2(\Lambda) + c_1 \frac{1}{16\pi^2}\Lambda^2 + c_2 \frac{1}{16\pi^2} \log\left(\frac{\Lambda}{M_{\rm ew}}\right) + \text{finite}$$

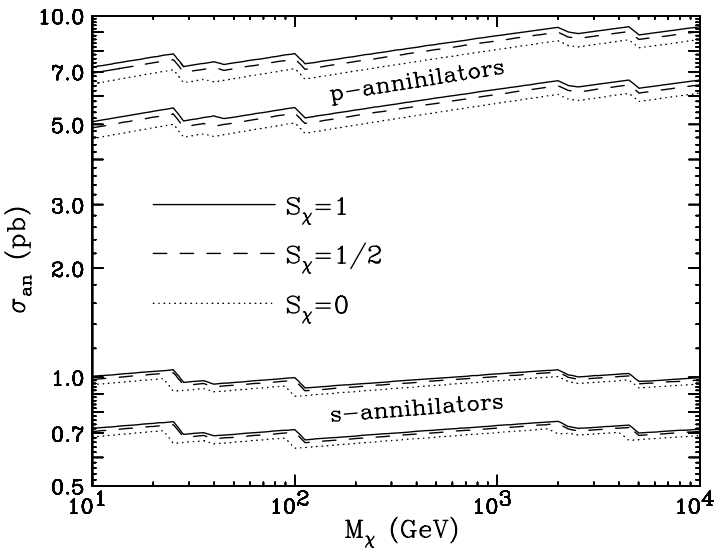
with $c_1 \sim 1$ and Λ is the scale where loop integrals are cut off by new physics

- Expect $\mu \sim \Lambda/(4\pi)$ ⇨ $\Lambda \sim 1$ TeV (naturalness)

[But NB: $\Lambda \sim 10$ TeV if 1% fine-tuning is allowed!]

Thermal Dark Matter

- Dark matter (non-luminous, non-baryonic, non-relativistic matter) well-established by a variety of independent astro observations, ~20% of the universe
- None of the SM particles can be dark matter
- Assume new particle, in thermal equilibrium with the cosmic plasma in the early universe
- Measured DM density ⇨ interaction cross section DM-SM



$$\sigma \approx 1 \text{ pb} \sim \frac{\alpha}{(\text{TeV})^2}$$

independent hint for new physics at the TeV scale!

[figure: Birkedal, Matchev, MP, hep-ph/0403004]

Options for New Physics @ TeV

- Models with light Higgs, addressing naturalness:
  - New particles, related to SM by symmetry, cut off loops (ex. SUSY, Little Higgs, gauge-higgs unification)
  - Higgs not elementary, bound state resolved at ~TeV (ex. warped [Randall-Sundrum] extra dimensions)
  - Point-like SM particles resolved as TeV-scale strings (ex. large extra dimensions)
- Models without light Higgs, necessarily strongly-coupled at the TeV scale (ex.: Technicolor, Higgsless)
- Models that do not improve naturalness, but have other interesting features or unusual signatures (ex. hidden valley, unparticles)

Supersymmetry

- In supersymmetric theories scalar masses do not receive quadratic divergences
- SUSY not symmetry of nature ⇒ must be broken
- "Soft" breaking at the TeV scale ⇒ loops cut off at the TeV scale, naturalness restored
- "Minimal" supersymmetric SM (MSSM): superpartner for each SM d.o.f., plus 2nd Higgs doublet and its superpartners

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Table 7.1: The undiscovered particles in the Minimal Supersymmetric Standard Model (with sfermion mixing for the first two families assumed to be negligible).

34 new particles waiting to be discovered!

[table: S. Martin, hep-ph/9709356]

MSSM and Its 100 Parameters

- Arbitrary soft terms ⇒ O(100) free parameters, affecting spectrum, branching ratios, etc.

$$
\begin{aligned}
\mathcal{L}_{\text{soft}}^{\text{MSSM}} \;=\; & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& - \left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d + \text{c.c.}\right) \\
& - \widetilde{Q}^\dagger\,\mathbf{m_Q^2}\,\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\,\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\,\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\,\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\,\widetilde{\overline{e}}^\dagger \\
& - m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - \left(bH_uH_d + \text{c.c.}\right).
\end{aligned}
$$

- Models of SUSY breaking "predict" some parameters (or relations among them), reduce the freedom

- But: Many such models (e.g. gravity mediation, gauge mediation, anomaly mediation, etc.), each has strengths and weaknesses, no clear "winner" emerged over ~25 years of model-building ⇒ NEED DATA!!!

- Search strategies must be designed with this in mind - "cover" the 120-dimensional parameter space as well as experimental limitations allow

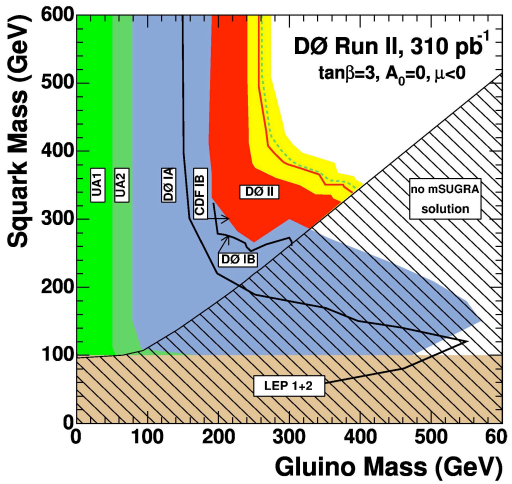
SUSY: Generic Predictions

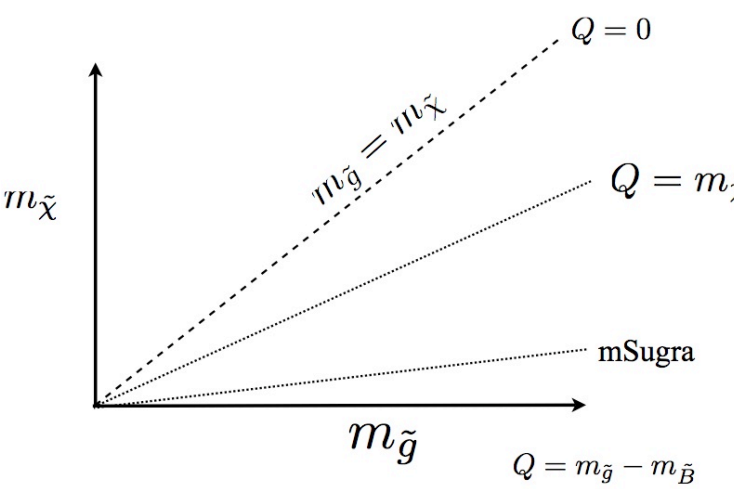
- Extra discrete symmetry - R parity - imposed to avoid rapid proton decay (may be relaxed, but very artificial)
- All SM states R-even, superpartners R-odd ⇒ lightest superpartner (LSP) stable
- Strong limits on colored/charged relics in the universe ⇒ prefer neutral LSP (also a WIMP dark matter candidate!)
- Generic signature: missing energy in every event with superpartner production
- But NLSP may be stable on time scale relevant to a collider detector: $t \sim L/c \sim 10^{-8}$ sec ! ⇒ Searches for long-lived charged and colored objects (e.g. staus and R-hadrons) are also well motivated
- Inclusive search for stable (neutral or not) objects plus high-pT jets and/or leptons is the best mod.-ind. strategy

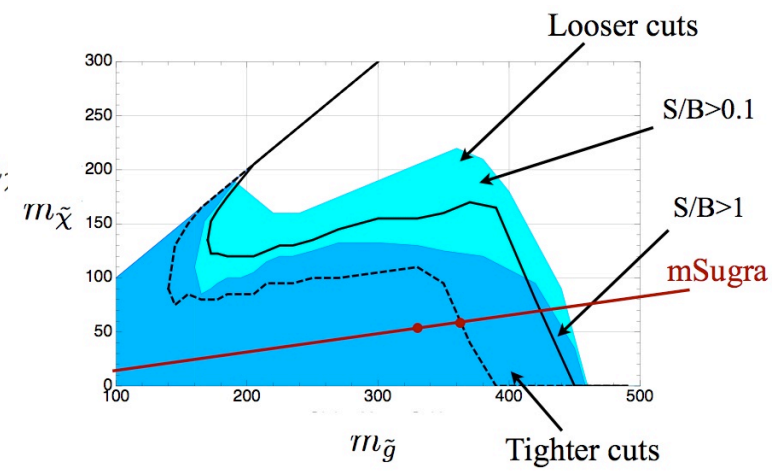
The Importance of Inclusiveness

- Experiments like to present results of searches as limits on model parameters
- 100+ par. framework impractical - choose a set of assumptions (mSUGRA most popular) to reduce to "a few"
- Advantage: Easy vocabulary to compare between experiments, both high-pT and others (g-2, EDMs, etc.)
- Disadvantage: Cuts optimized to maximize bounds in this framework, may miss a signal!!!

[Ex.: D0 squark/gluino search (Alwall et. al., 0803.0019)]







MSSM and Naturalness

- Non-observation of the Higgs at LEP2 presents a significant problem for the MSSM
- At tree level, a firm upper bound (ind. of 120 parameters) on the mass of the lighter CP-even Higgs boson: $m(h^0) < M_Z$
- Experimentally, $m(h^0) > 114\ \mathrm{GeV}$ (except corners)
- Loop corrections to $m(h^0)$ must be large (25%)
- Same loops induce large corrections to Higgs vevs, which need to be canceled precisely - fine-tuning of O(1%)

[possible way out: Choi et al, hep-ph/0508029; Kitano, Nomura, hep-ph/0509039]

- If SUSY is realized, it may well be a non-minimal version (e.g. extra scalars coupled to the Higgs sector, non-standard Higgs phenomenology - see S. Chang's talk tomorrow)

Quantum Gravity at TeV

- At Planck scale, SM has to be embedded into a theory with quantum gravity - string theory?
- It is believed that that theory must be finite - all divergences cut off at $M_{\rm Pl}$
- If $M_{\rm Pl} \sim 1\ {\rm TeV}$, there is no hierarchy problem!
- ADD model: SM on a 4D brane inside higher-D space, with extra dimensions compactified with

$$R \sim M_{\rm Pl}^{-1} \left(\frac{M_{\rm Pl,4}}{M_{\rm Pl}} \right)^{2/n} \gg M_{\rm Pl}^{-1}$$

- At $E < M_{\rm Pl}$, model-independent missing energy signature due to graviton emission into the extra dimensions
- If two partons collide at super-plankian energies $E \gg M_{\rm Pl}$, a black hole must form (and decay promptly)

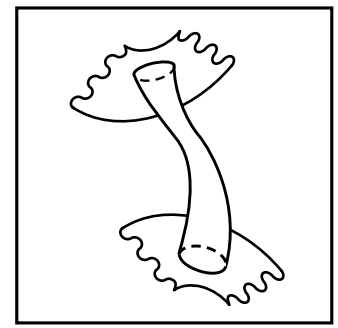
String Theory at TeV

- Given existing constraints on $M_{\rm Pl}$, it seems pretty unlikely that the LHC will probe the region $E \gg M_{\rm Pl}$

[Meade, Randall, 0708:3017]

- In any (weakly coupled) string theory, Regge excitations of SM particles lie below Planck scale

$$M_n = \sqrt{n} M_S, \qquad M_S \ll M_{\rm Pl}$$



- Reggeons appear as s-channel resonances in SM scattering processes!

[Cullen, MP, Peskin, hep-ph/0001166]

- Easy to see, more realistic target than BHs
- Distinguish from Zprimes etc.: spin $S = S_0 + n$, e.g. first "Regge gluon" is spin-2!
- Excited Reggeons have spin > 2 ⇒ at present not handled by general-purpose MC generators!

QCD Redux: Composite Higgs, Technicolor, and Their Cousins

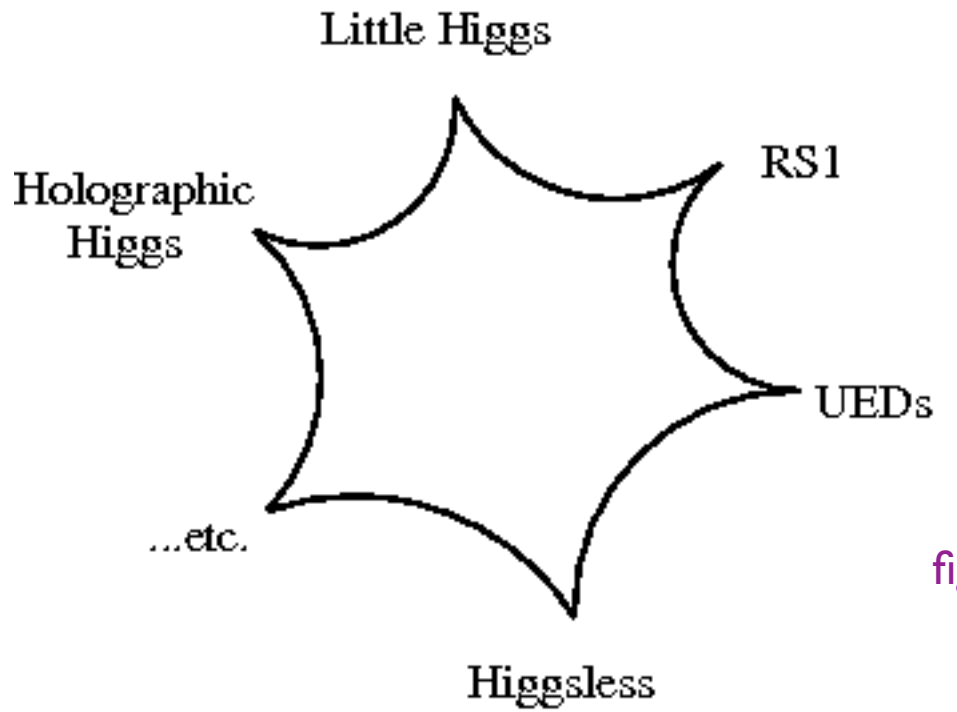


figure credit: Ian Low

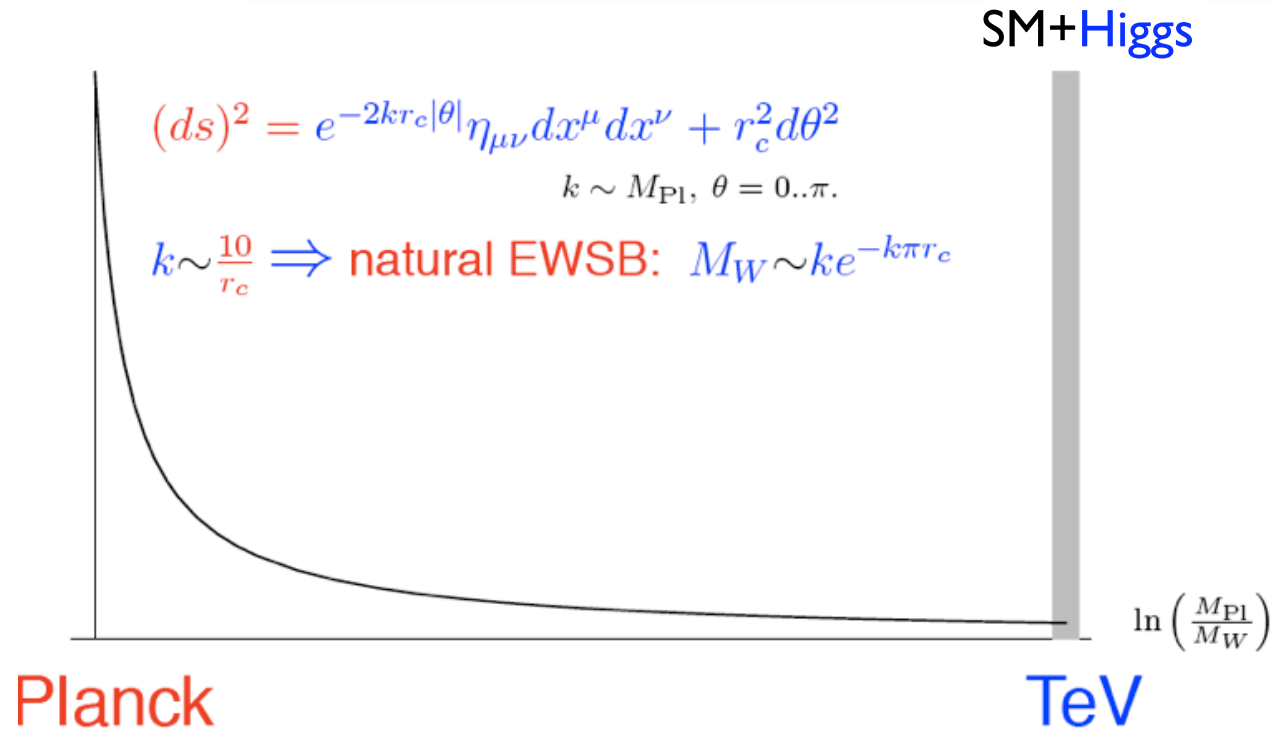
- All these models involve new strong dynamics at TeV (or 10 TeV), a la QCD confinement at GeV, but with interesting new twists!

Composite Higgs

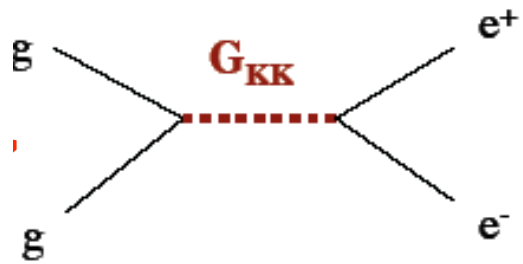
- Many spin-0 particles exist in nature - mesons
- They are composite, made of spin-1/2 quarks, bound by QCD strong force
- Above the QCD confinement scale, the good degrees of freedom are quarks ⇨ no hierarchy problem!
- Can the Higgs be a meson bound by a new strong force?
- Old idea, but difficult to build models - non-perturbative physics!
- New insight: AdS/CFT duality ⇨ some strongly coupled 4D models are "dual" to weakly coupled, calculable models with an extra dimension!
- Setup: Randall-Sundrum (RS) 5D model

Warped (RS) Extra Dimension

- Original model had the SM on the TeV brane, solves the hierarchy problem

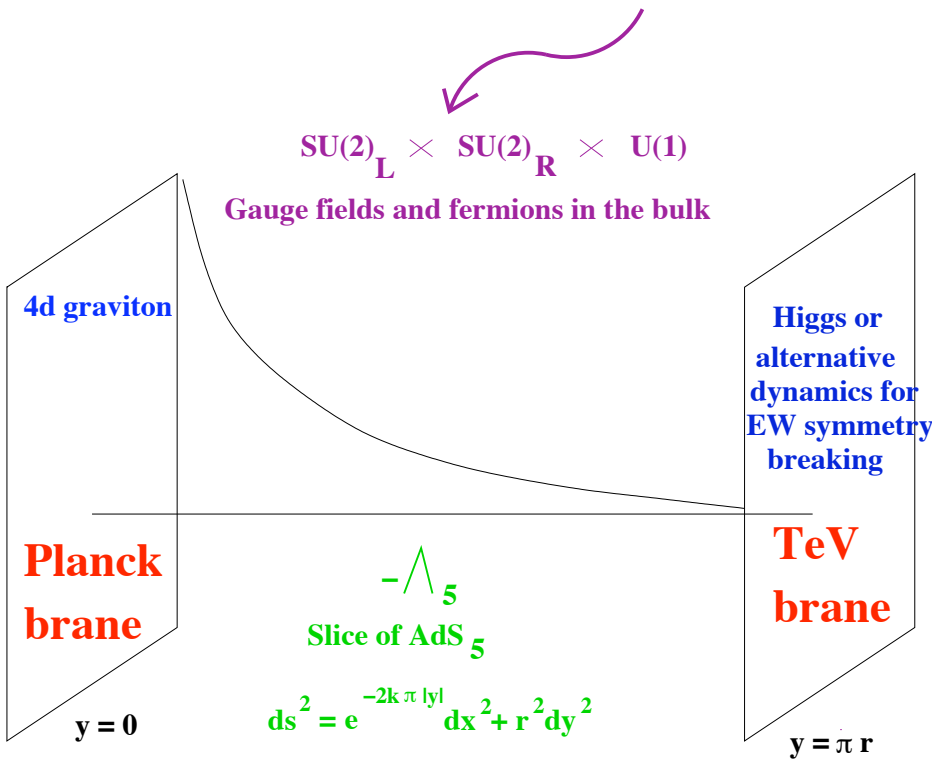


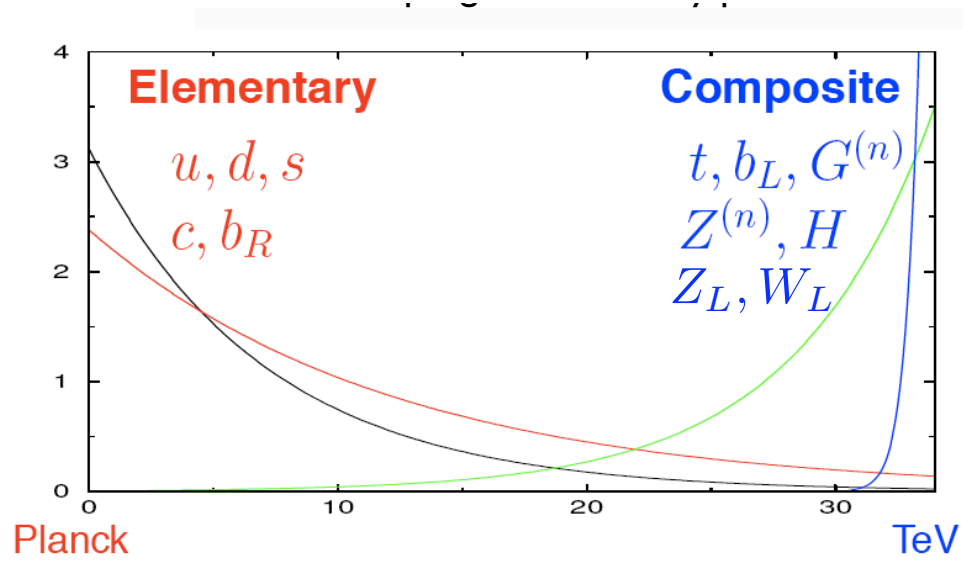
- New states: KK gravitons at the TeV scale
- Couplings: $\mathcal{L} \sim \frac{1}{(\mathrm{TeV})^2} T_{\mu\nu} G^{\mu\nu}_{\rm KK}$



RS with Bulk Matter

- It was subsequently realized that models with SM gauge fields and fermions in the "bulk" are more interesting:





- natural solution to fermion mass hierarchy problem

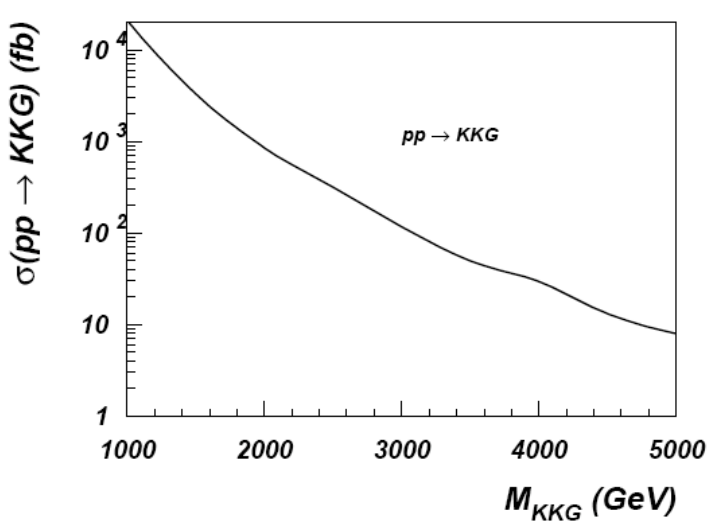
- natural suppression of flavor-changing neutral currents

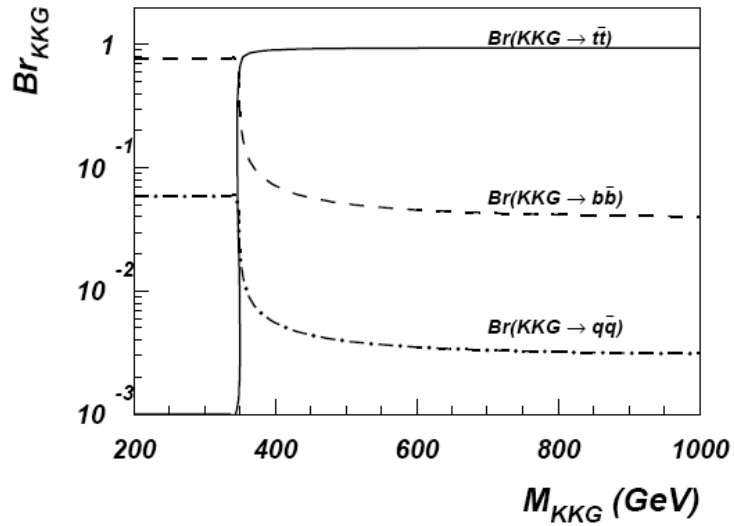
- possibility of gauge coupling unification, as in the MSSM

figure credits: G. Perez, G. Servant

RS with Bulk Matter: Pheno

- Good: all SM states now have KK modes!
- Bad: the KKs do not couple to light quarks and leptons much...
- Worse: PEW constraints force KK masses > 3 TeV or so
- KK gluon is probably the easiest target at the LHC



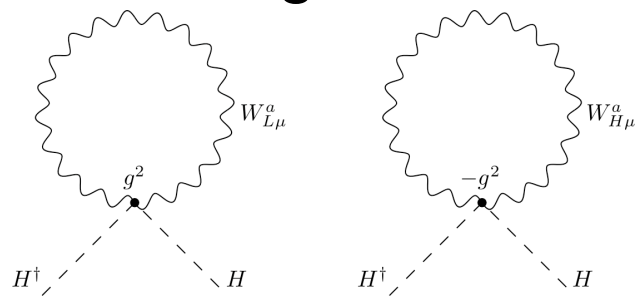


Agashe et. al., hep-ph/0612015; Lillie et.al., hep-ph/0701166

Final state: A pair of highly-boosted tops ("top jets"?)

Gauge-Higgs Unification

- A zero-mass photon does not require fine-tuning - mass is protected by gauge symmetry
- In a 5D theory, the gauge field $A_M(x) \to A_\mu(x), A_5(x)$
- If the 5th dimension is infinite, A_5 is naturally massless!
- After compactification, $m(A_5) \sim 1/R$ ⇨ good if $1/R \sim M_W \sim M(W')$
- Higgs mass quadratic divergences are canceled by KK modes:



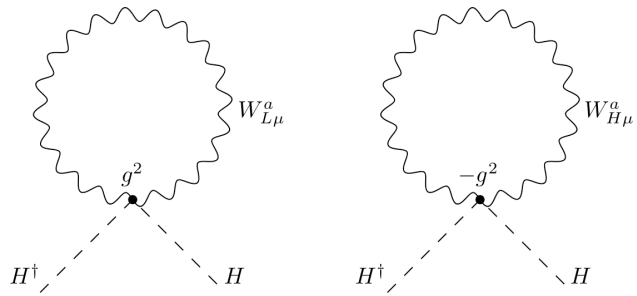
- A realistic GHU implementation, using a warped extra dimension, predicts $m_h < 140$ GeV and KK states at 2 TeV

[Agashe, Contino, Pomarol, hep-ph/0412089]

Little Higgs

- Quadratic divergence cancellation by same-spin states can also occur in a purely 4D theory - Little Higgs

[LH ⇔ effective theory of the first two KK modes in GHU!]

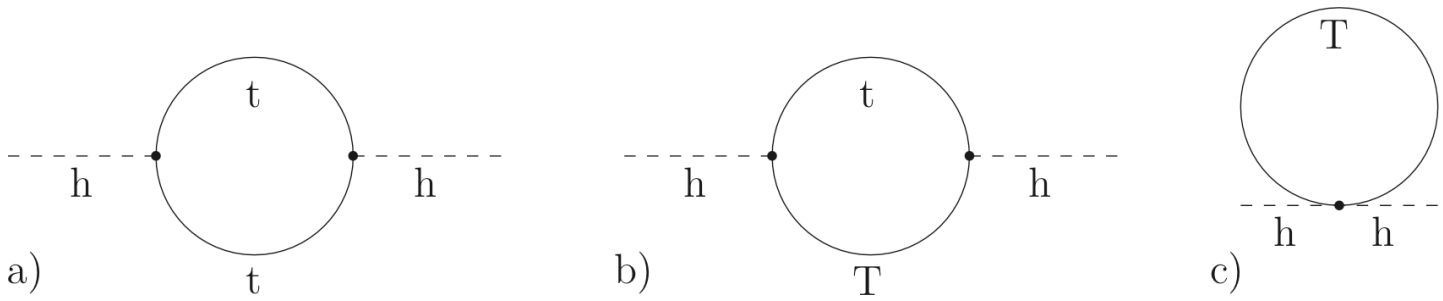


- In LH, Higgs is a Goldstone boson arising from a global symmetry breaking [a la pions in QCD]
- If the global symmetry is exact, $m_h = 0$ naturally!
- Goldstones only interact derivatively ⇒ need to break the global symmetry explicitly by gauge and Yukawa interactions
- Generically explicit breaking reintroduces quadratic divergences
- "Collective" breaking pattern in LH avoids quad. div. at one loop

[Arkani-Hamed, Cohen, Georgi, 2002]

EWSB in Littlest Higgs Model

- Higgs mass is dominated by top and Top loops:



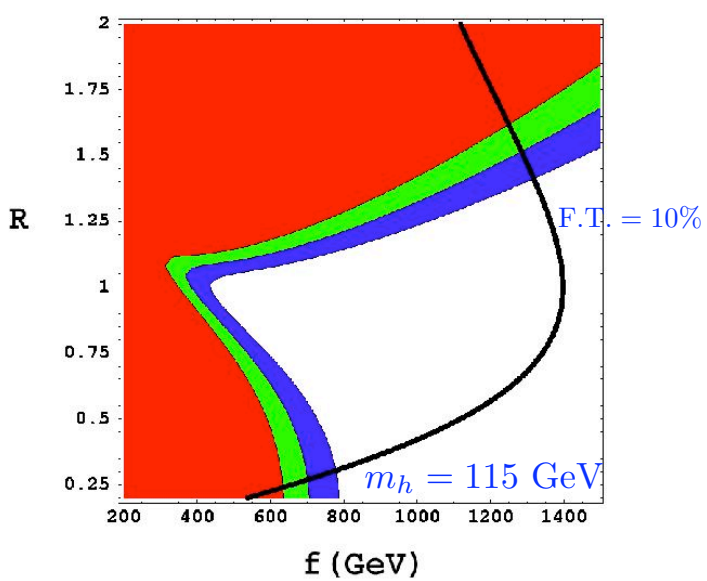
- This contribution is log-divergent and negative:

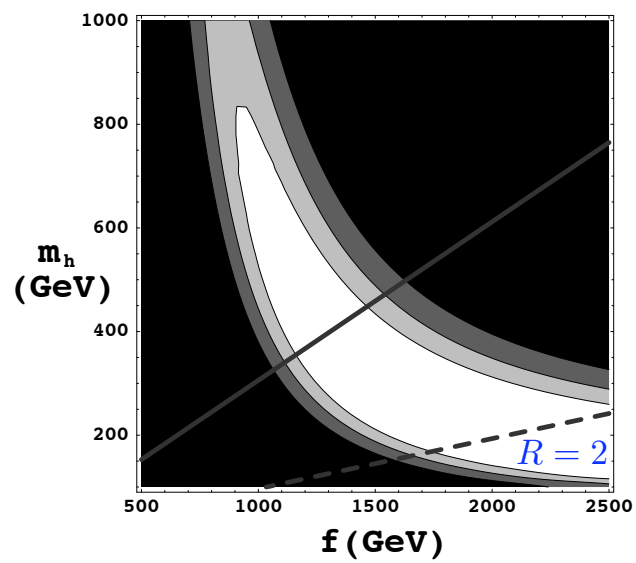
$$m_{\rm t}^2(H) = -\frac{3\lambda_t^2 M_T^2}{8\pi^2}\log\frac{\Lambda^2}{M_T^2} \ .$$

- All other contributions are generically subdominant
- EWSB is triggered radiatively - simple mechanism!
- Similar to the MSSM but with no tree-level potential at all - e.g. no μ problem!

Little Higgs and T Parity

- LH models are weakly coupled at the TeV scale, predictive!
- The "first-generation" LH models strongly disfavored by precision electroweak data
- Best solution: introduce "T Parity": new TeV-scale particles T-odd and only appear in loops in PEWO [a la R parity of the MSSM]
- Littlest Higgs with T Parity (LHT) passes PEW tests without significant fine-tuning

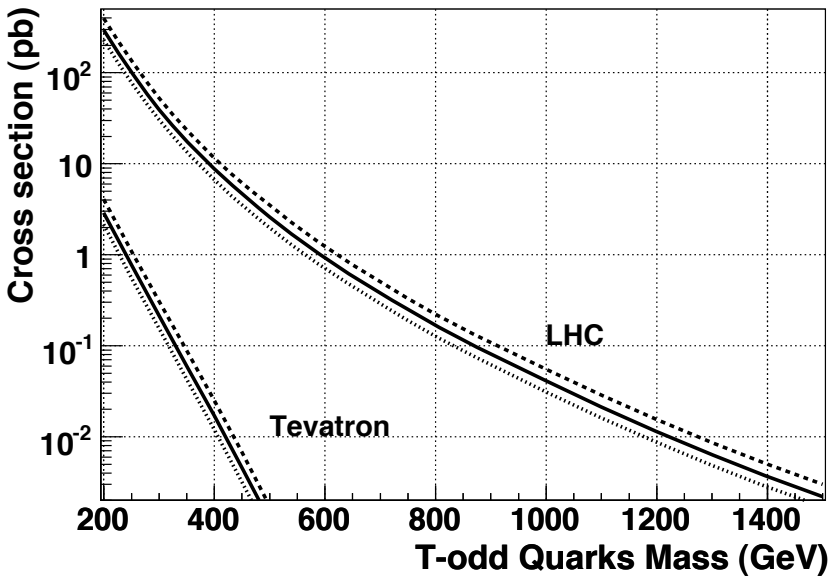


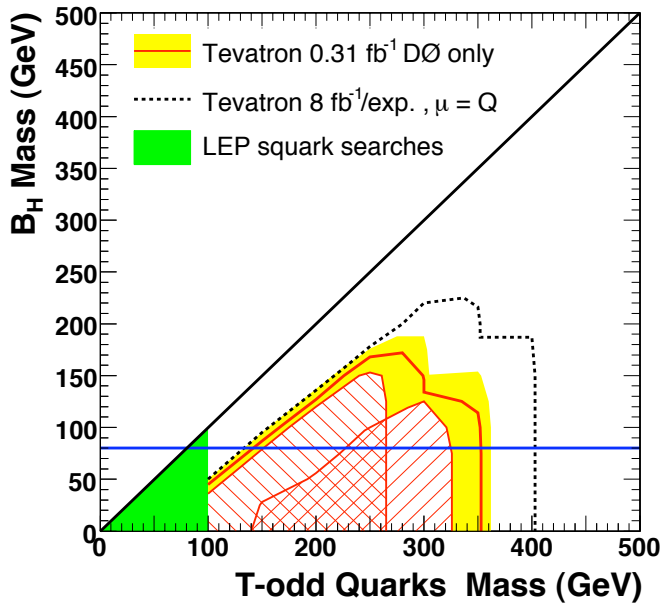


[Hubisz, Meade, Noble, MP, hep-ph/0506042]

LHT Collider Phenomenology

- The Lightest T-Odd Particle (LTP) is stable, typically the neutral, spin-1 "heavy photon" - WIMP DM candidate
- Symmetry structure forces introduction of T-odd partners for each SM (weak doublet) fermion - "T-quarks" and "T-leptons"
- Hadron collider signature: T-quark production, decays to LTP+jets





[Carena, Hubisz, MP, Verdier, hep-ph/0610156]

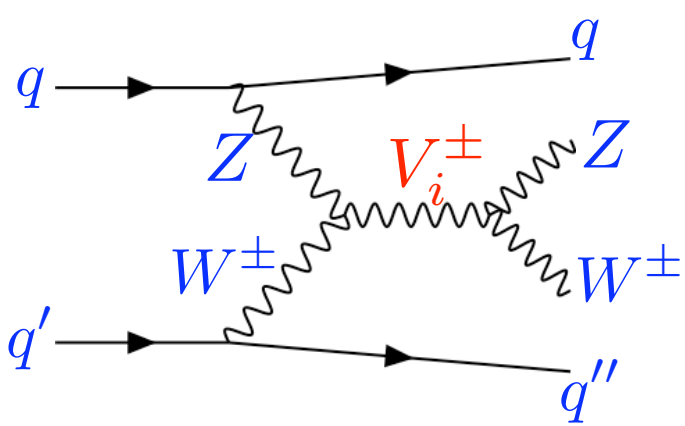
Another "SUSY look-alike" candidate!

What if There is No Higgs?

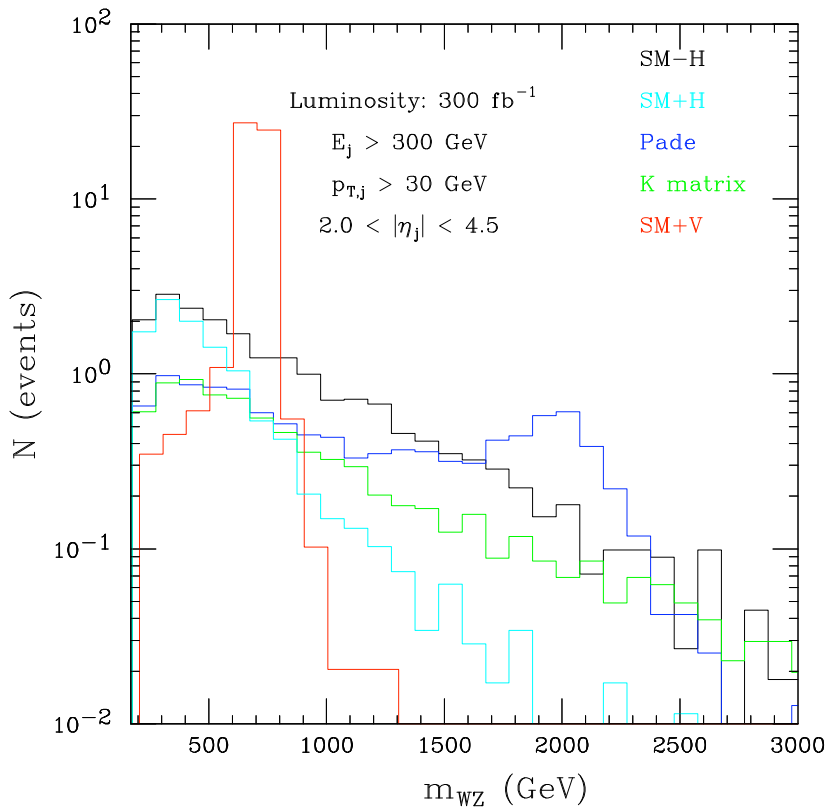
- If physics at TeV scale is strongly coupled, a symmetry-breaking condensate can exist without a physical Higgs boson in the theory - technicolor!
- TC with QCD-like dynamics at TeV is strongly disfavored by precision electroweak data
- Difficult to explore model space due to strong coupling
- New insight: AdS/CFT duality ⇨ some strongly coupled 4D models are "dual" to weakly coupled, calculable models with an extra dimension!
- 5D "Higgsless" models have been constructed, with EWSB by boundary conditions in RS-like setup, passes precision electroweak tests with ~1% fine-tuning
- Fermion masses can be straighforwardly incorporated

Higgsless Phenomenology

- Best place to search for all higgsless models is W/Z scattering
- Unitarity must be restored, typically resonances appear
- 5D Higgsless model predicts narrow, light (sub-TeV) resonances



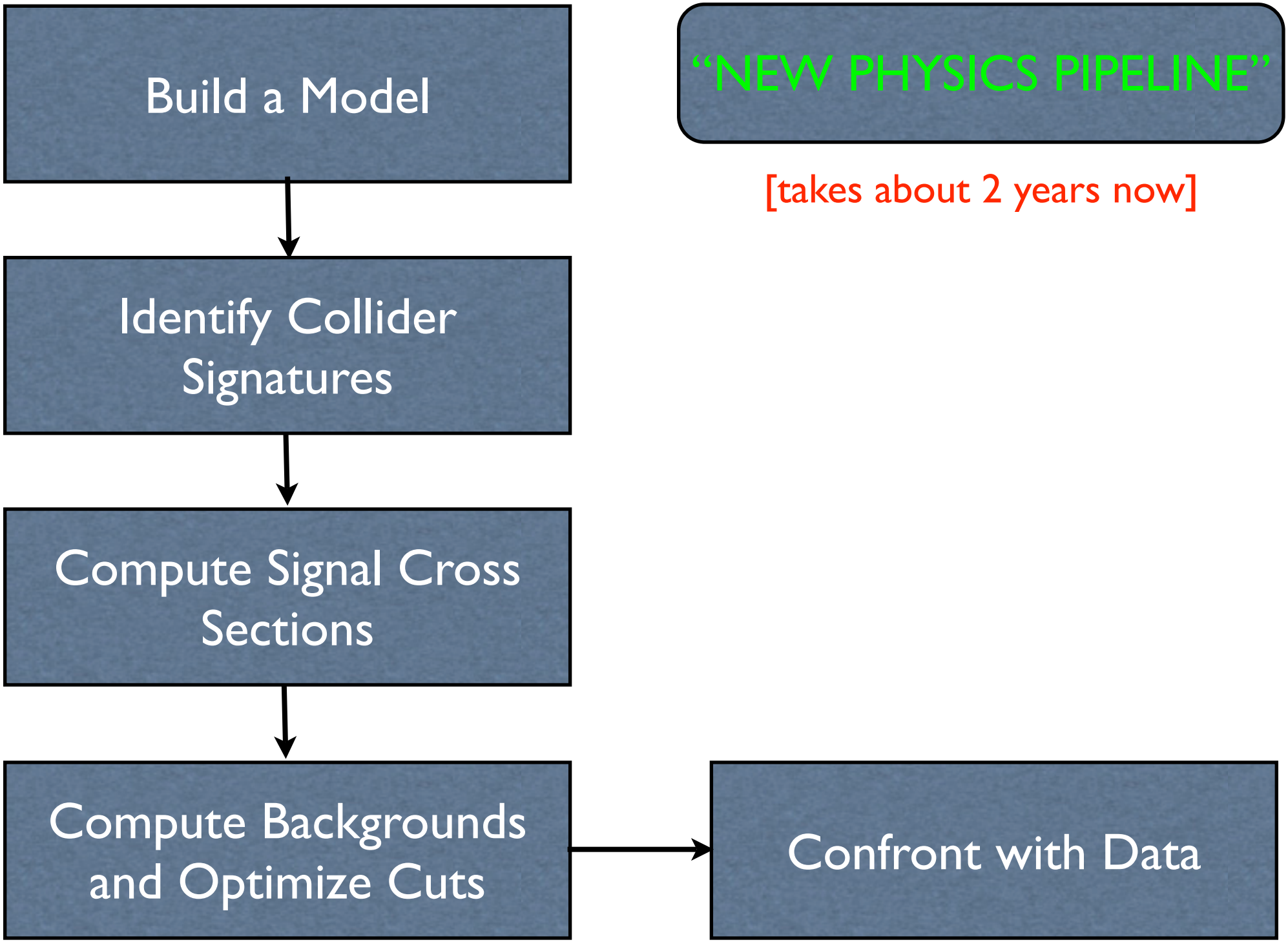
[Birkedal, Matchev, MP, hep-ph/0412278]

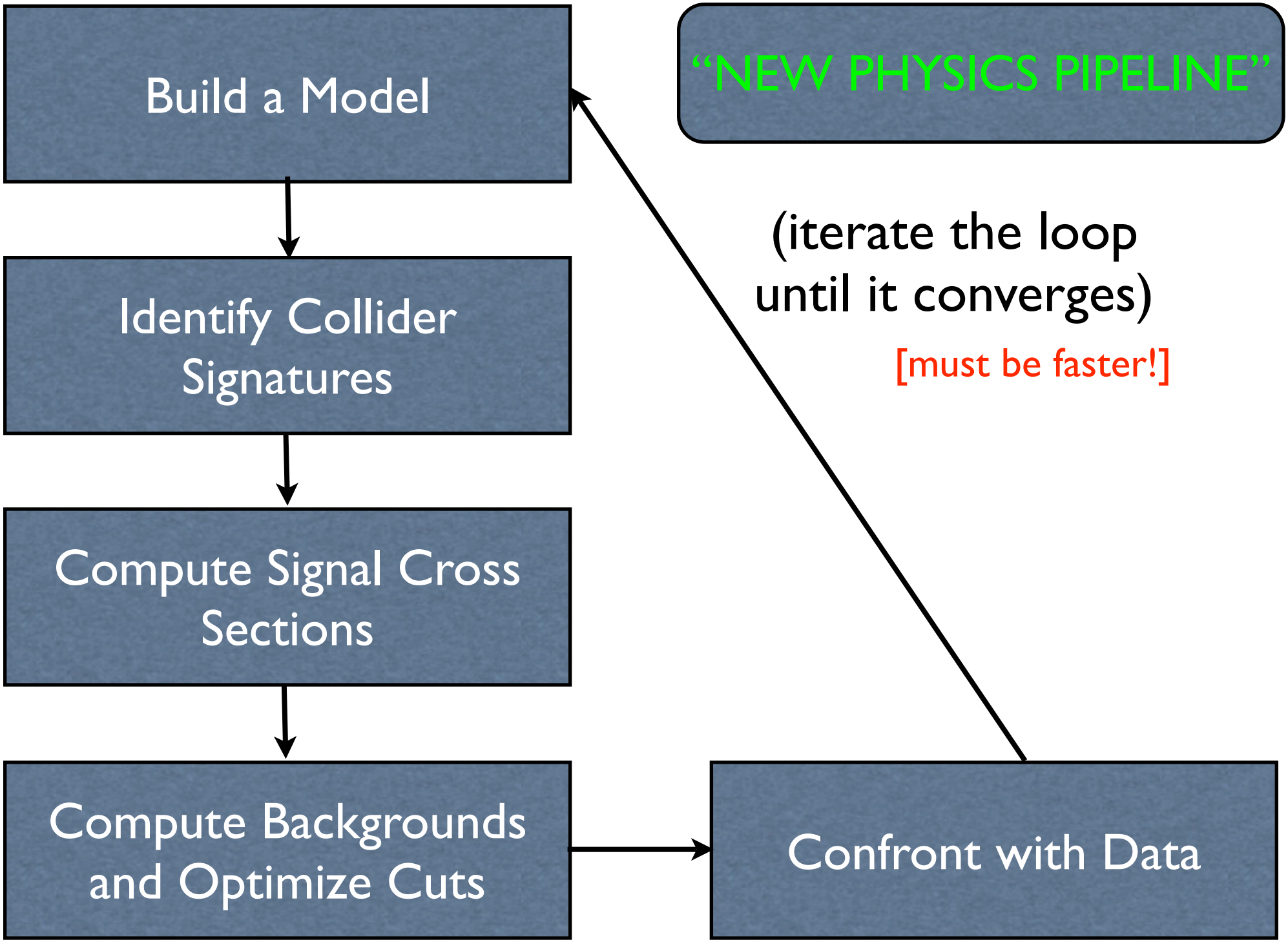


Gold-Plated Channel: 2j+3l+Et_miss

Closing Remarks

- Since the SM became accepted (~30 years), theorists have been able to provide very precise guidance for new physics searches at the energy frontier (e.g. W, Z, top)
- This is NOT the case in the BSM physics hunt:
  - Number of "ideas" is finite (SUSY, xdim, TC, ...)
  - Number of "implementations" is essentially infinite
  - Number of "free parameters" in each implementation is typically large
- Inclusive (signature-based whenever possible) searches are the best bet
- "Model space" will evolve very quickly once there is evidence for BSM in the data!


Build a Model
Identify Collider Signatures
Compute Signal Cross Sections
Compute Backgrounds and Optimize Cuts
Confront with Data
"NEW PHYSICS PIPELINE"
[takes about 2 years now]


Build a Model
Identify Collider Signatures
Compute Signal Cross Sections
Compute Backgrounds and Optimize Cuts
Confront with Data
"NEW PHYSICS PIPELINE"
(iterate the loop until it converges)
[must be faster!]

Conclusions

- The mechanism which breaks electroweak symmetry remains a fundamental, unsolved mystery
- All natural models of EWSB predict new physics at the TeV scale
- Tevatron is at the frontier, discovery possible every day
- LHC is on its way!
- Lots of interesting possibilities - exciting physics ahead!
- Widely open theory space brings challenges as well:
  - Making sure no new physics is missed (triggers, cuts)
  - Experiment-theory communication issues